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Broadband 1.2- and 2.4-mm Gallium Nitride (GaN) Power Amplifier Designs

by John E Penn

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Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT The US Army Research Laboratory is exploring devices and circuits for radio frequency communications, networking, and sensor systems of interest to Department of Defense applications, particularly for next-generation radar systems. Broadband, efficient, high-power monolithic microwave integrated circuit amplifiers are extremely important in any system that must operate reliably and efficiently in continually crowded spectrums, with multiple purposes for communications, networking, and radar. This report describes the design of a broadband Class A/B power amplifier using Raytheon's high-frequency, efficient, gallium nitride on 4-mil silicon carbide process. While this design was not part of the initial wafer fabrication for the original effort, it could be finalized and fabricated at a future date.			
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I would like to acknowledge and thank the Raytheon team, especially Steve Bernstein, Steve Lardizabal, Rob Leoni, and Ken Wilson for the design support, computer-aided design support, technical expertise, and fabrication of these gallium nitride (GaN) circuits for emerging Department of Defense systems and applications. The ARL team of Edward Viveiros, Ken McKnight, Ali Darwish, Abigail Hedden, and John Clark provided their expertise and support in the design of these GaN designs in the Raytheon process.

1. Introduction

The US Army Research Laboratory (ARL) has been working with Raytheon to design efficient, broadband, linear, high-power amplifiers and robust, broadband, low-noise amplifiers for future adaptive, multimodal radar systems. Raytheon has a high-performance, W-band, gallium nitride (GaN) fabrication process and a process design kit (PDK) that researchers at ARL used to design low-noise amplifiers, power amplifiers, and other circuits for future radar, communications, and sensor systems. After the first set of ARL and Raytheon designs were submitted to fabrication, I performed a couple test designs of broadband Class A/B power amplifiers. While these designs did not get fabricated in the initial effort, they serve to demonstrate the performance, bandwidth, and capability of this GaN process and could potentially be fabricated in the future.

2. Broadband Power Amplifier

This report documents the preliminary design of a single high-electron mobility transistor (HEMT) and 2-way parallel combined HEMT power amplifier. These initial broadband power amplifiers are based on a 12×100-µm HEMT at a nominal recommended DC bias. This size HEMT had an optimal match provided by Raytheon as “RLoad” ohms in parallel with a negative “CDS” pF in capacitance. Since a negative reactance can only be matched over a limited band, an initial design was performed of an ideal, double, tuned, Q bandpass match for broadband operation centered around 4.5 GHz, with a goal of achieving 2 to 10 GHz. A schematic of the ideal load as a resistor in parallel with a capacitor and the ideal, double, tuned output matching circuit is shown in Fig. 1. The simulation from 2 to 10 GHz of the ideal load (blue S11 trace) and ideal bandpass match (magenta S11 trace) are shown in the Smith chart plot (Fig. 2).

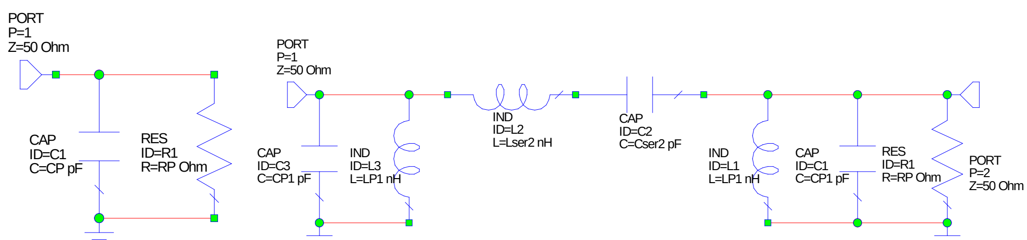

Fig. 1 Microwave Office (MWO) schematic for the ideal power load and match (12×100-µm HEMT—nominal DC bias)

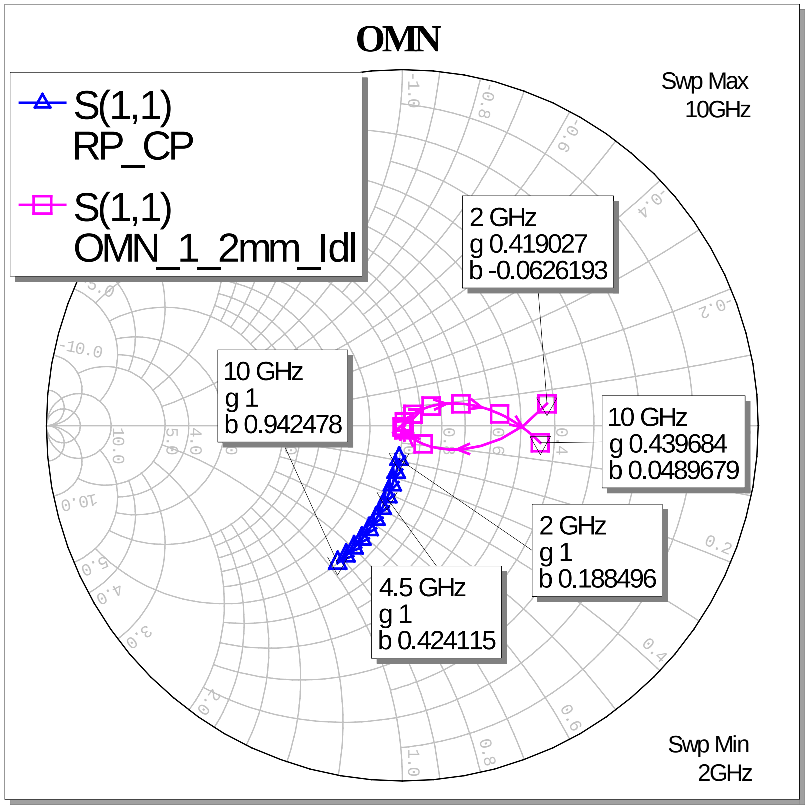

Fig. 2 MWO simulation of the ideal power load and match (12×100-µm HEMT—2 to 10 GHz)

After designing an ideal, lumped-element output match, the capacitors and inductors were replaced with monolithic microwave integrated circuit (MMIC) elements from the Raytheon GaN design library and retuned to achieve a broadband match. Then microstrip bends, tees, and decoupling elements for the DC bias were added to complete a layout of the MMIC output match (Fig. 3). A simulation of the output match (Fig. 4) shows a better than 20-dB return loss from 2.3 GHz to above 8.7 GHz (purple trace) versus the ideal, lumped-element, double, tuned match with slightly less bandwidth (magenta trace) but an excellent match midband.

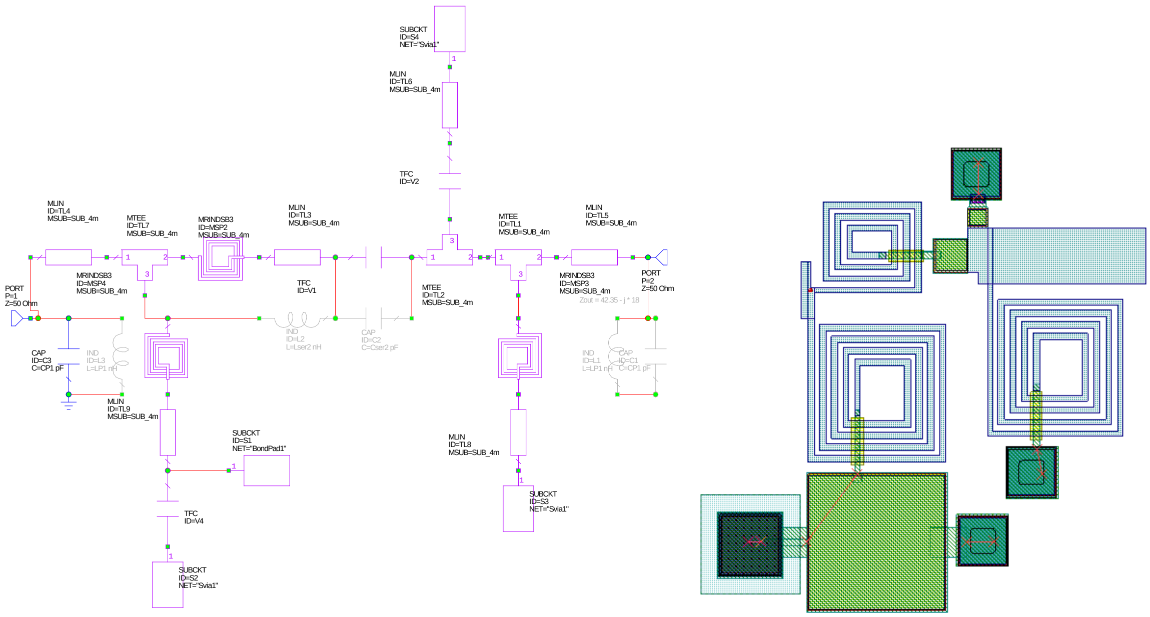

Fig. 3 Schematic and MMIC layout of the broadband matching circuit (12×100-μm HEMT)

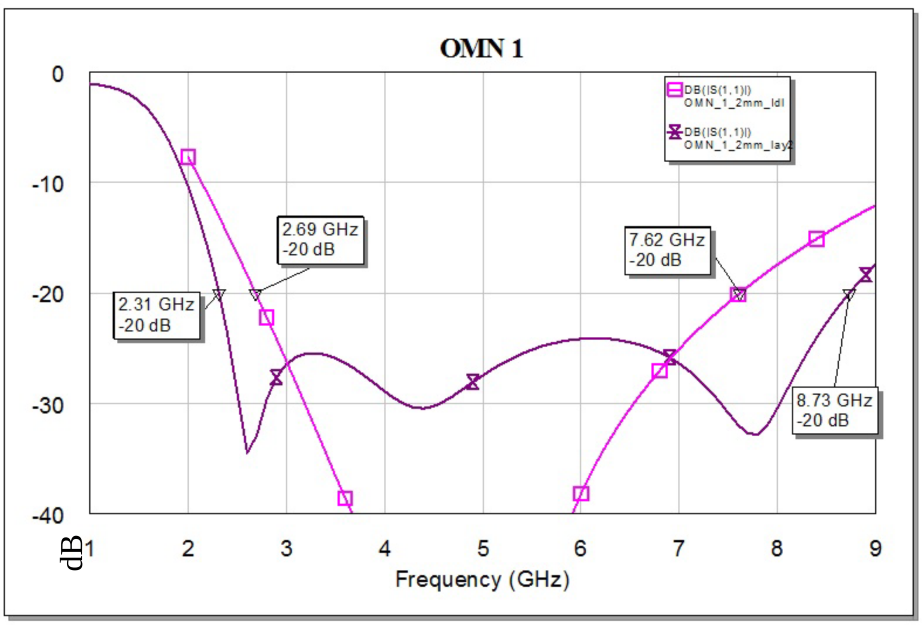

Fig. 4 MWO simulation of the ideal (magenta) and MMIC output match (purple)

Comparing the impedance match of the ideal, lumped-element output match (solid lines) to the lossy MMIC output match (dotted lines) over frequency to the ideal "RLoad" normalized impedance (left axis) and negative "CDS" normalized capacitance (right axis) shows good broadband performance (Fig. 5). The ideal output match is close to the ideal "RLoad" load line of a 1.2-mm HEMT from 3.5

to 6 GHz, while the MMIC output match undershoots the real part of the impedance but stays very close to 95% of RLoad over a broader range of 3 to 7 GHz. Since an ideal reactance equivalent to a negative “CDS” capacitance can only be maintained over a finite bandwidth, the output matching circuits can be seen as matching well over the band, diverging at the low end of the frequency range (2 to 3 GHz). Resistances (left axis) in the plot are represented by shades of red and magenta, while capacitances (right axis) are represented by shades of blue.

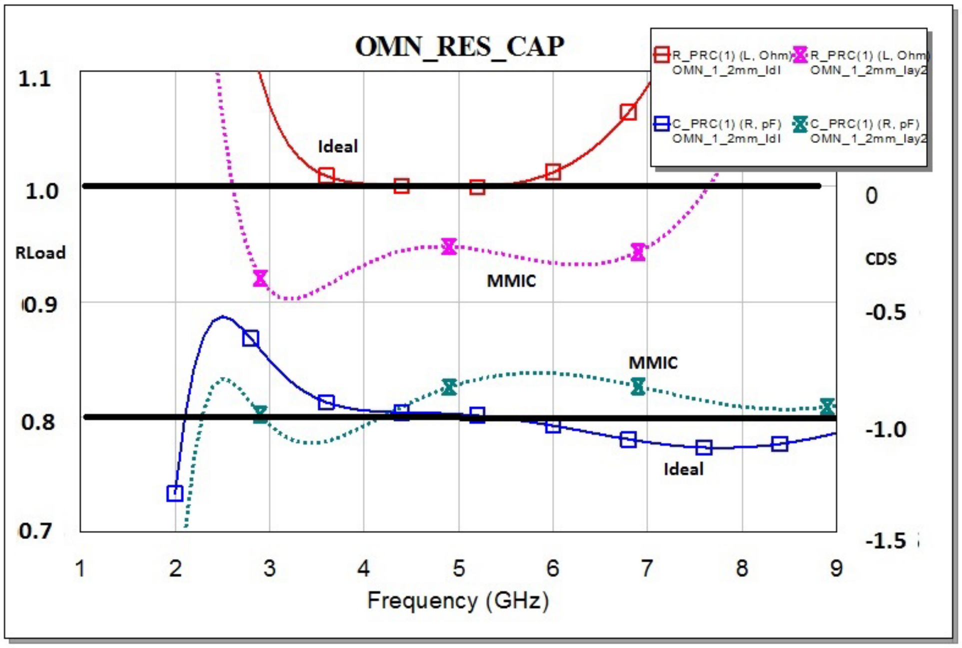

Fig. 5 Broadband impedance of output match ideal (solid) vs. MMIC (dotted) (RLoad || -CDS)

After designing the output match for the broadband power amplifier, the S-parameters of the 12×100-µm (1.2-mm) HEMT are generated at the nominal DC bias. Initially, these S-parameters were exported from Advanced Design System (ADS) (Fig. 6) and imported into MWO to perform an initial amplifier design. Small-signal stability was analyzed and establish with a shunt resistor and a parallel series resistor and capacitor on the gate of the HEMT. Figure 7 shows that the source stability circles are all outside the Smith chart, indicating unconditional stability. After stabilizing the 1.2-mm HEMT, the input impedance at midband (4.5 GHz) was simulated resulting in a higher Q matching impedance (Q = 2.4) than the output, making it more difficult to broadband match the power amplifier input. An initial ideal input match provided better than 10-dB return loss from 3.5 to 6 GHz, but was limiting the amplifier bandwidth compared to the output matching circuit. An ideal, coupled line provided a broader frequency range for the input match, while sacrificing additional loss. A compact, spiral, coupled line was a technique suggested by the Raytheon team to provide broadband match, but at these frequencies requires significant area in the MMIC layout. A preliminary ideal transmission line input matching circuit provided good performance from 2 to 7 GHz (Fig. 8). The ideal input matching elements were replaced with MMIC components resulting in 2 relatively large inductors. Next, the folded, spiral, coupled line requires electromagnetic (EM) simulation to verify its performance.

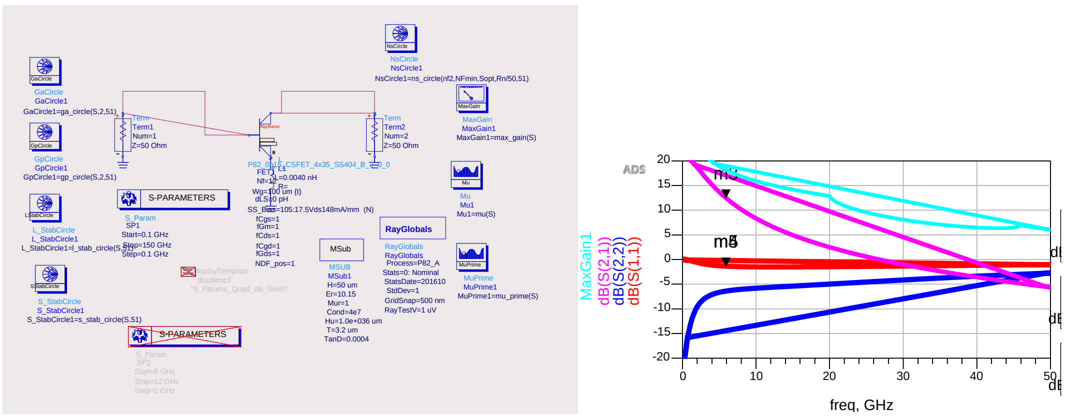

Fig. 6 ADS S-parameter simulation of the 12×100-µm (1.2-mm) GaN HEMT

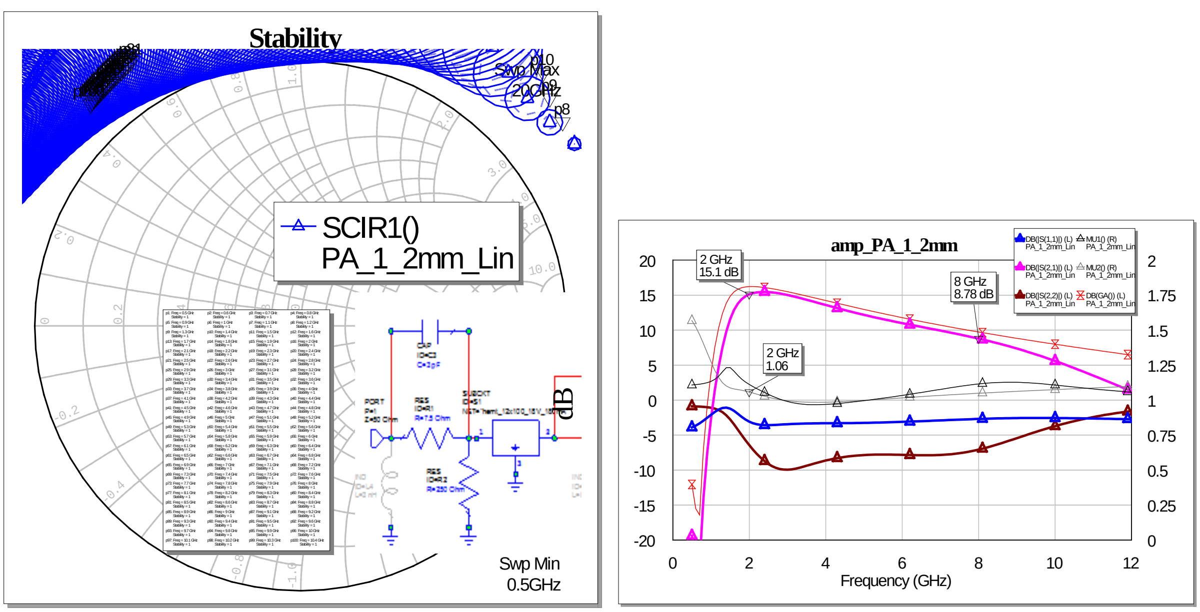

Fig. 7 Stabilizing resistors added to the 12×100-µm GaN HEMT plus broadband output match

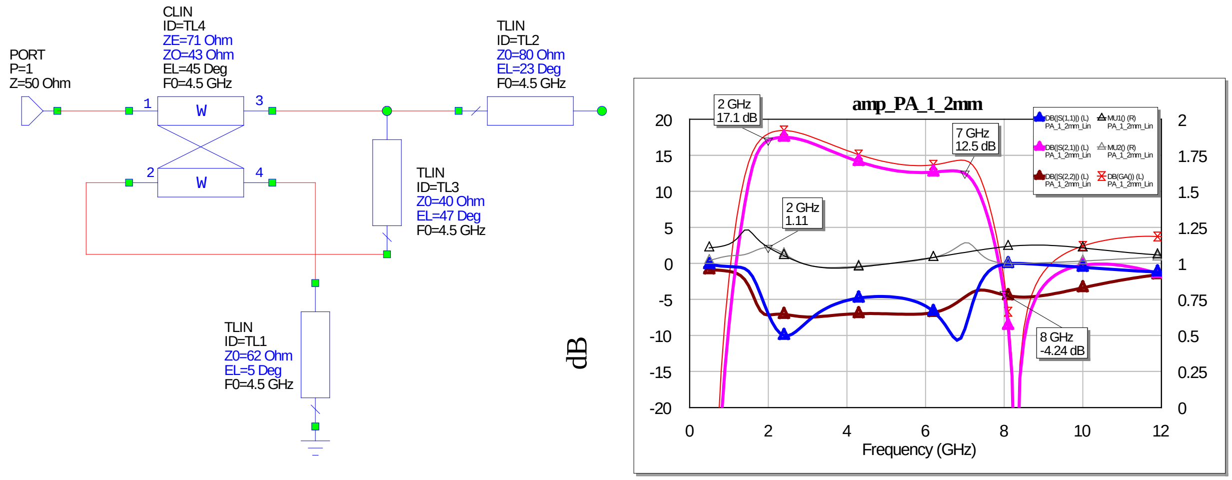

Fig. 8 Ideal, coupled line input match for the 2- to 7-GHz, 1.2-mm GaN HEMT power amplifier

A preliminary input match including DC bias input for the gate is shown in Fig. 9. A pseudo layout of the full one-stage, 1.2-mm, 2- to 8-GHz power amplifier is shown in Fig. 10; note the large area required for the broadband input match. The resulting single-stage amplifier performance is shown in Fig. 11, with good gain at 2 GHz, dropping gradually to 10 dB at 8.5 GHz.

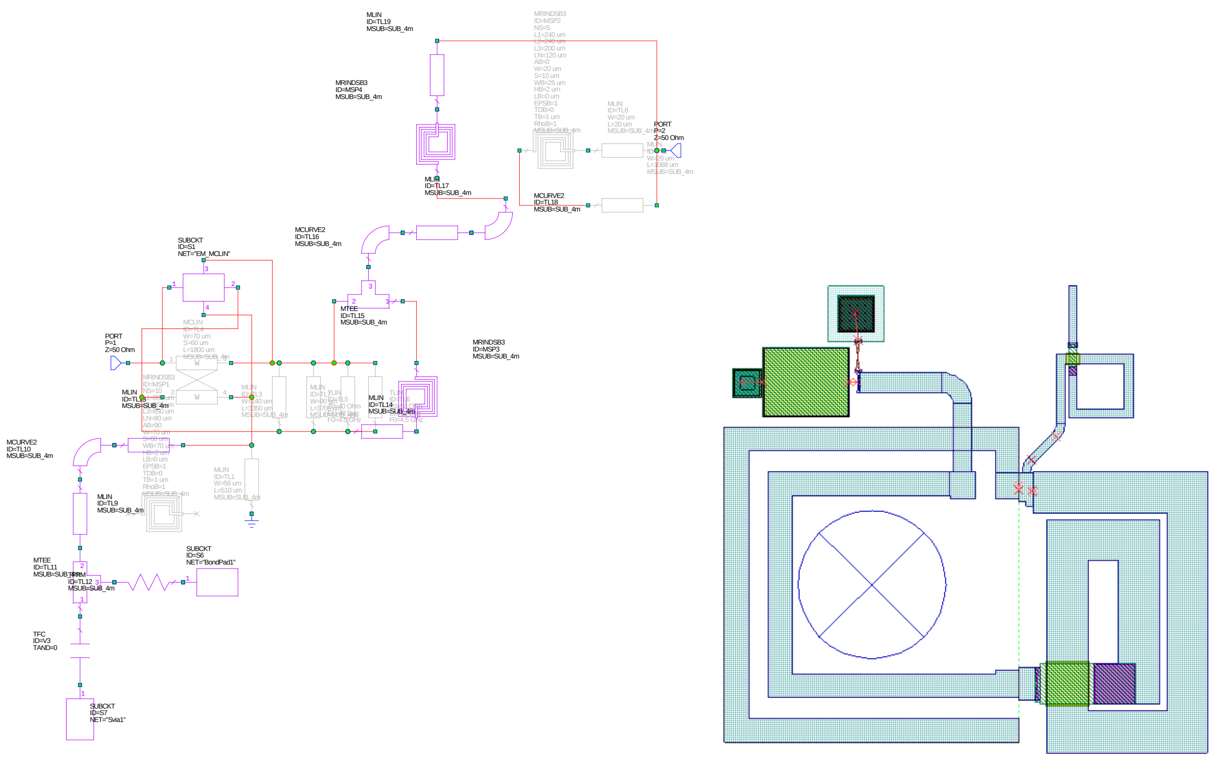

Fig. 9 Broadband, compact, folded, coupled line MMIC input match for the 2- to 8-GHz, 1.2-mm GaN HEMT power amplifier

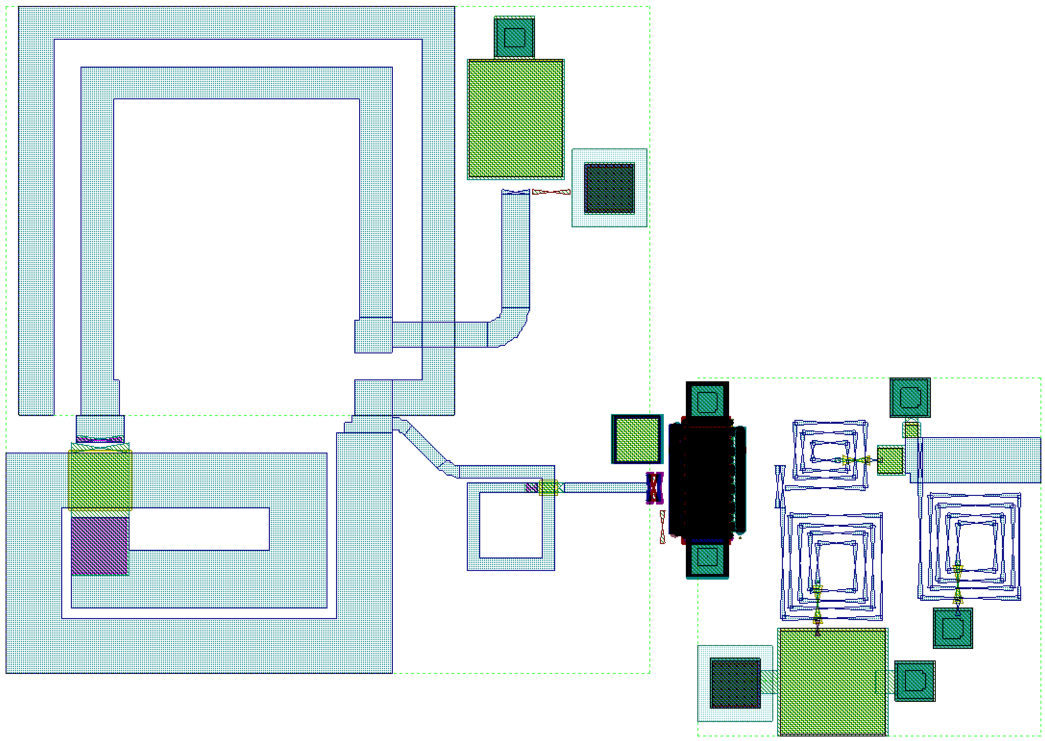

Fig. 10 Unfinished layout of the broadband (2- to 8-GHz), 1.2-mm GaN HEMT power amplifier

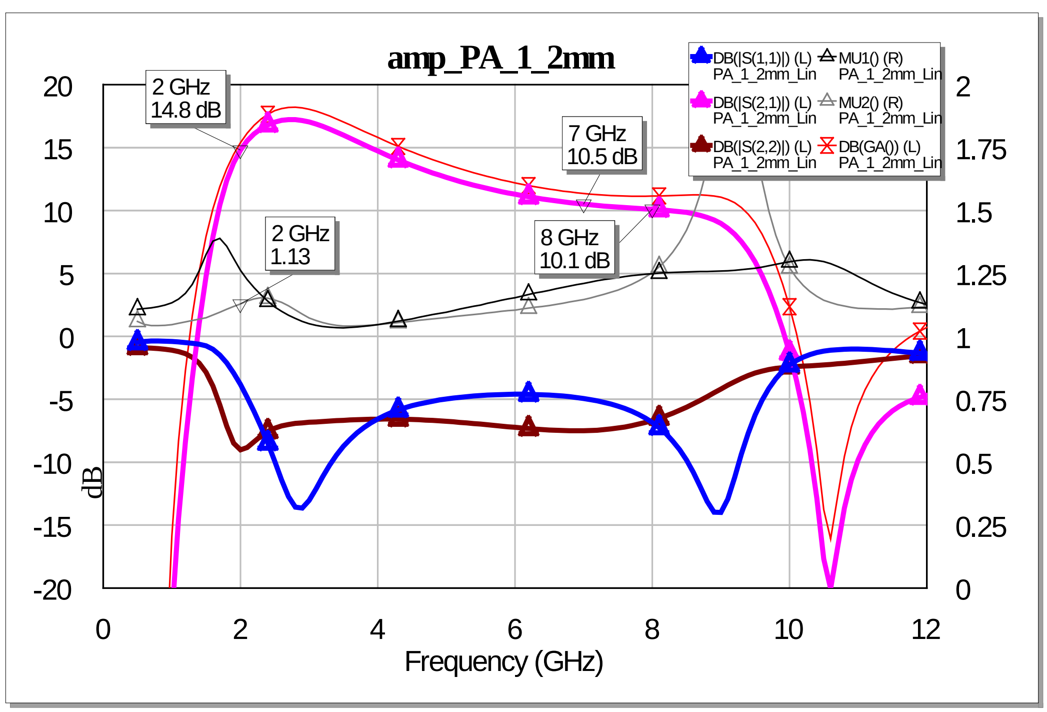

Fig. 11 Small-signal simulation of the broadband (2- to 8-GHz), 1.2-mm GaN HEMT power amplifier

With a preliminary layout and MWO simulations for a stable, broadband power amplifier from 2 to 8 GHz based on a 1.2-mm GaN HEMT, the next step was to perform nonlinear simulations using the design kit and ADS. The nonlinear HEMT model within the ADS Raytheon design kit is needed to do performance simulations. MWO schematics for the MMIC input and output circuits were translated into ADS schematics. Ideal bias tees were added to provide the DC bias as a convenience to simulating the ADS schematics (Fig. 12), though the matching circuits have the appropriate components for DC and RF decoupling. This power amplifier design would still need design rule checks (DRCs), layout versus schematic (LVS), and final EM simulations. If another fabrication opportunity appears, this is a good starting point and could be easily completed using the circuits documented in this technical report.

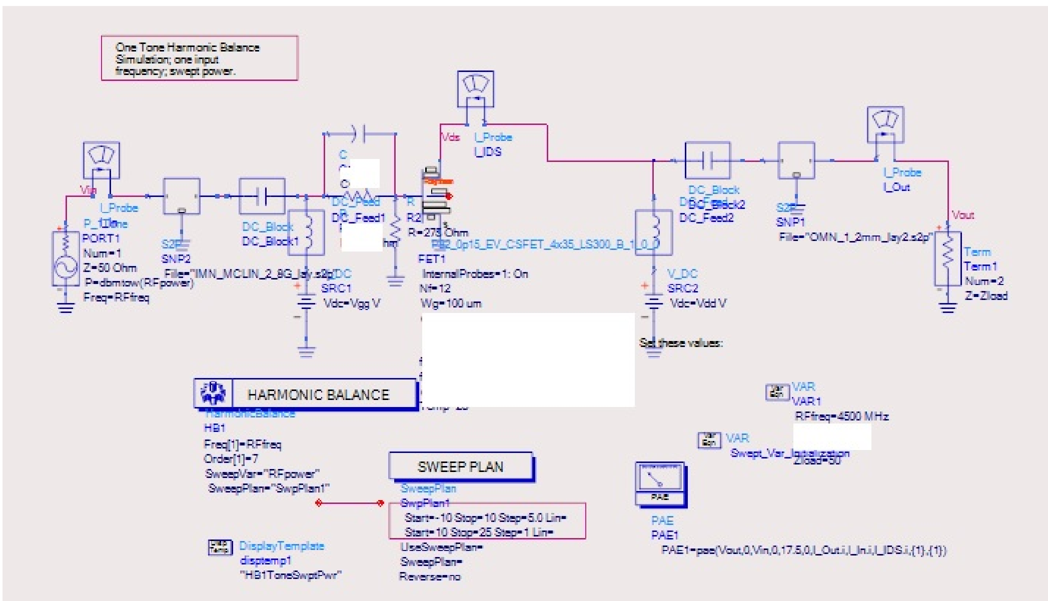

Fig. 12 ADS simplified schematic of the 4- to 5-W, broadband (2- to 8-GHz), 1.2-mm GaN HEMT power amplifier

A dynamic load line simulation at the center frequency of 4.5 GHz for the one-stage power amplifier at nominal DC bias is shown in Fig. 13. Performance simulations for power-added efficiency (PAE) and output power at the center frequency of 4.5 GHz are shown in Fig. 14, with output power within 0.6 dB of ideal for a 1.2-mm HEMT. As an additional verification, ADS was used to repeat the small-signal S-parameter simulations, but with the nonlinear HEMT model at the nominal DC bias. The gain seems a little higher than the previous simulations in MWO, but the return loss and gain with frequency has a similar shape, as expected. To get a measure of the losses due to the physical MMIC output, input, and matching circuits, an ADS schematic of the power amplifier using the original lossless element input and output matching circuits was simulated. Output power and efficiency is slightly higher in comparison for the broadband, 1.2-mm HEMT power amplifier with lossless matching elements. Figure 15 shows the performance simulation at the center frequency of 4.5 GHz, for the lossless, matched, 1.2-mm HEMT single-stage power amplifier. Performance simulations for PAE and output power with an ideal lossless matching circuit at the center frequency of 4.5 GHz are shown in Fig. 16, with output power equal to that expected for a 1.2-mm HEMT and PAE of 56%–57%. A summary table (see Table 1, shown later in this section) compares the relative performance for the ideal lossless and lossy MMIC one-stage, 1.2-mm HEMT power amplifier at various frequencies, as well as a lossless 2-way parallel, combined, 2.4-mm HEMT power amplifier.

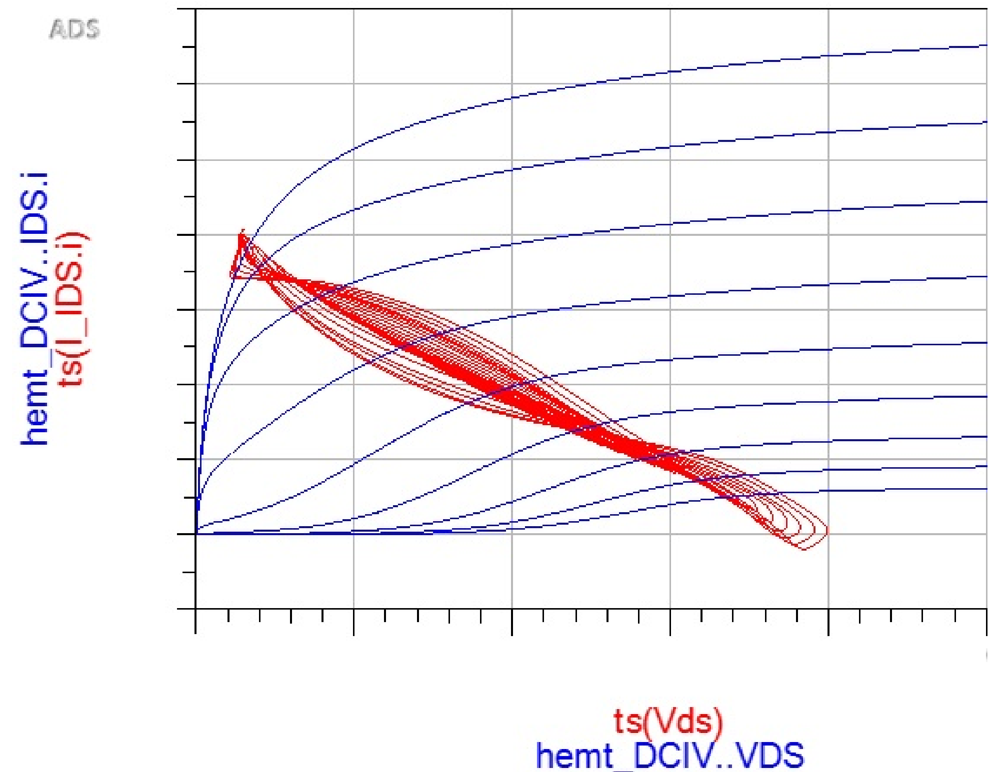

Fig. 13 ADS dynamic load line simulation of the broadband (4.5-GHz), 1.2-mm HEMT power amplifier

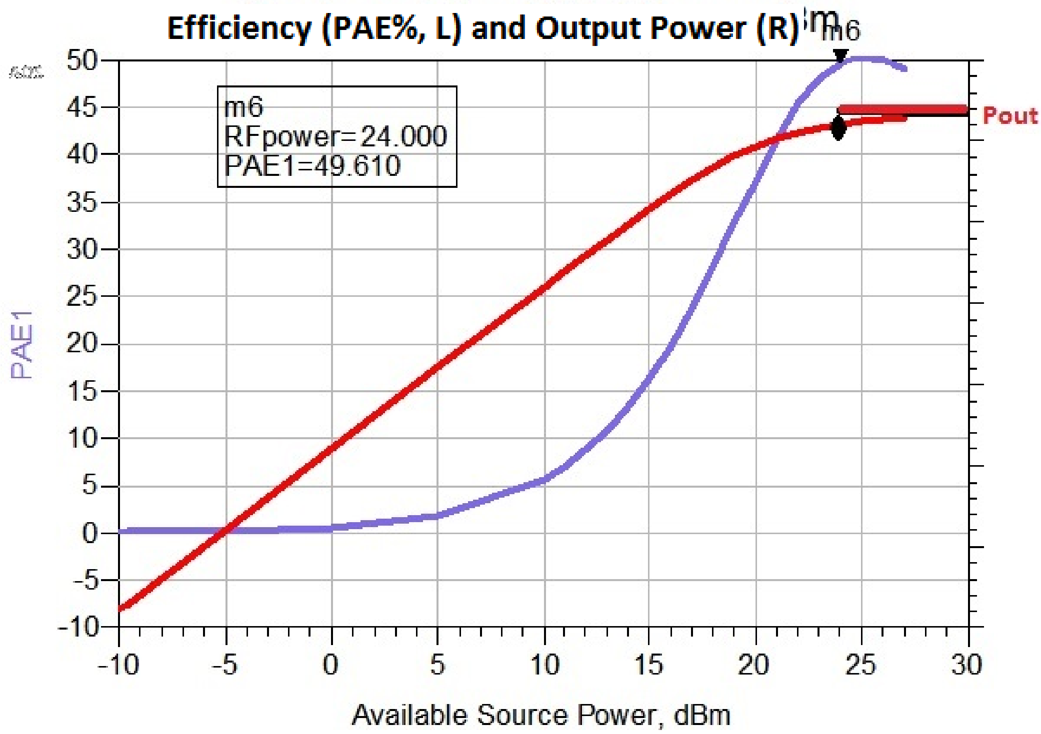

Fig. 14 ADS performance simulation of the broadband (4.5-GHz), 1.2-mm HEMT power amplifier

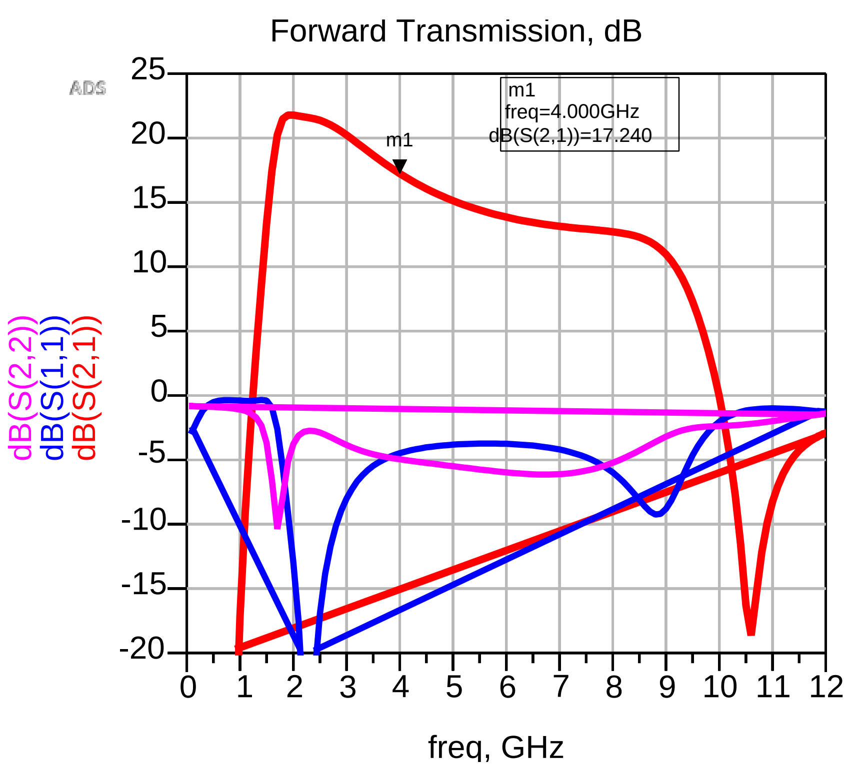

Fig. 15 ADS small-signal simulation of the broadband (2- to 8-GHz), 1.2-mm GaN HEMT power amplifier

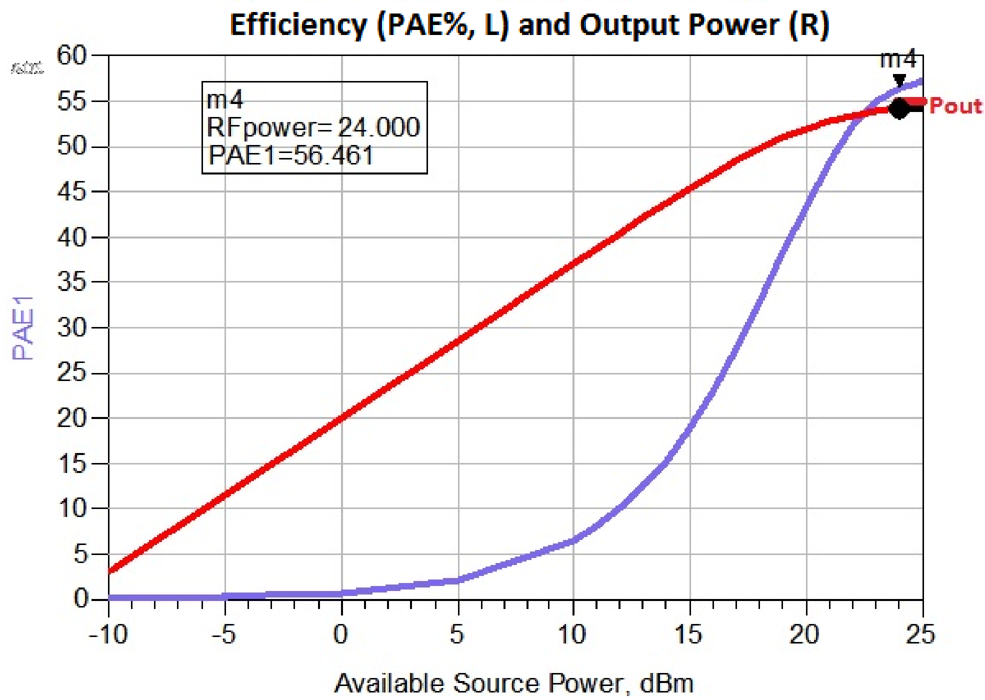

Fig. 16 ADS performance simulation of the ideal broadband (4.5-GHz), 1.2-mm HEMT power amplifier

In addition to the 1.2-mm broadband power amplifier, a 2.4-mm power amplifier was implemented using 2 parallel combined 1.2-mm HEMTs. First, the ideal output match for a single 1.2-mm HEMT was transformed from a 50-Ω output match to 100 Ω so that 2 devices could be easily paralleled into a 50-Ω load. Figure 17 shows the ideal broadband output match from a single 1.2-mm HEMT transformed to a 100-Ω output match, as well as the composite schematic of the 2-way combined output match (Fig. 18). This simple lossless combiner circuit would need to be modified to supply DC bias, and there are a several easy ways to modify it. The 2-way combiner output matching circuit has the same broadband return loss, with a better than 20-dB return loss match to the ideal load from 2.7 to 7.6 GHz (Fig. 19).

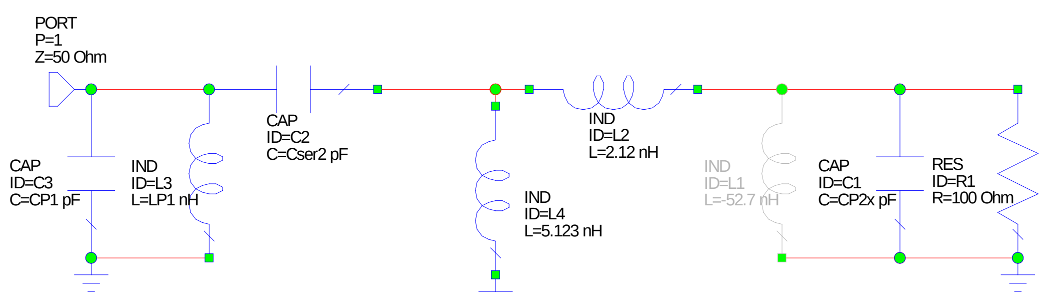

Fig. 17 MWO partial schematic for the ideal, parallel, 2-way combined circuit (12×100-µm HEMT)

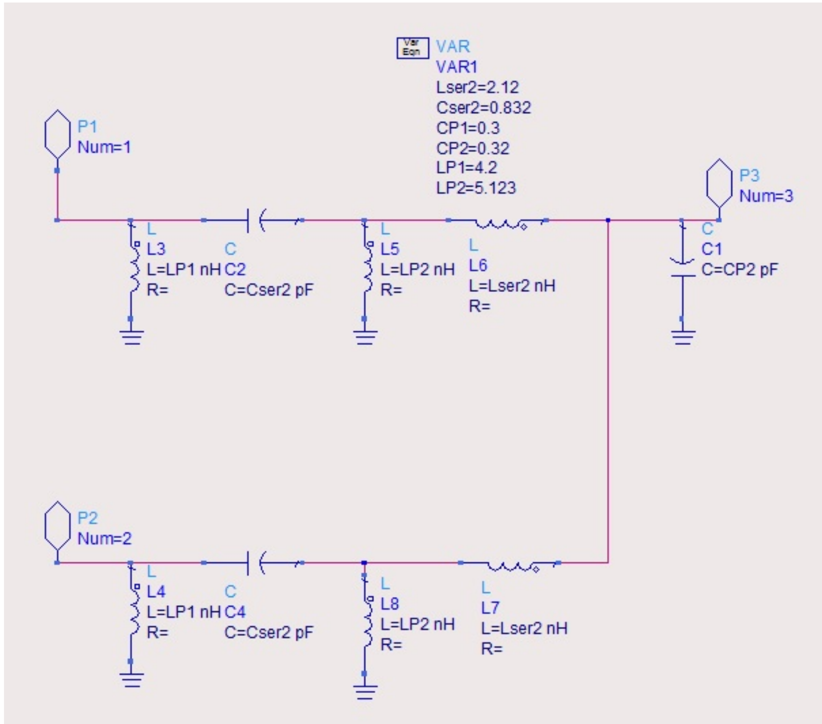

Fig. 18 **ADS schematic for the ideal, parallel, 2-way combined circuit (2- to 1.2-mm HEMTs)**

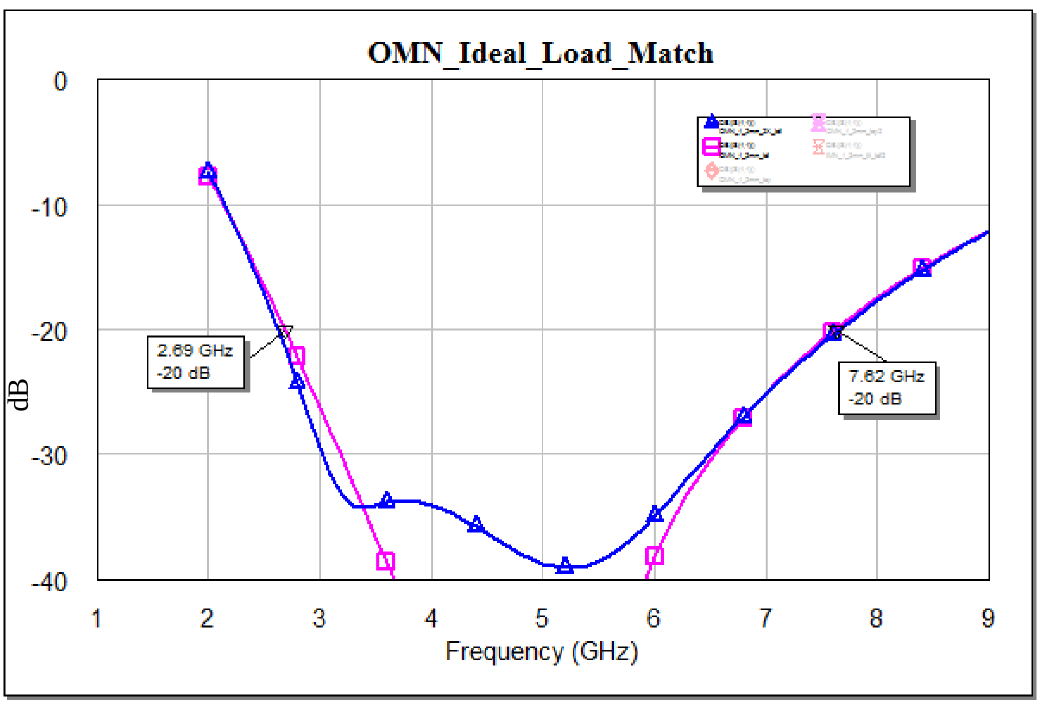

Fig. 19 **Double, tuned, ideal load match for the parallel, 2-way combined circuit vs. the single HEMT**

ADS was used to simulate the performance of the broadband power amplifier as a 2-way combined (2.4 mm) HEMT power amplifier using the ideal output matching circuit from Fig. 18. The input of the 2-way combined amplifier was simulated as 2 of the coupled line, ideal, input matching circuits into a 25-Ω source. An input matching circuit into a 50-Ω source would require a redesign but should not change the gain or bandwidth of the 2.4-mm power amplifier. Output power would be expected to double (+3 dB), with similar efficiency and bandwidth in comparison to the single 1.2-mm HEMT power amplifier. Figure 20 shows the performance simulation at the center frequency of 4.5 GHz, with output power equal to that expected and PAE of 55% for a lossless matched broadband, 2.4-mm HEMT single-stage power amplifier. A summary showing relative performance for the ideal lossless and lossy MMIC one-stage, 1.2-mm HEMT power amplifier at various frequencies, as well as an ideal, lossless, 2 parallel combined (2.4-mm) HEMT power amplifier are shown in Table 1.

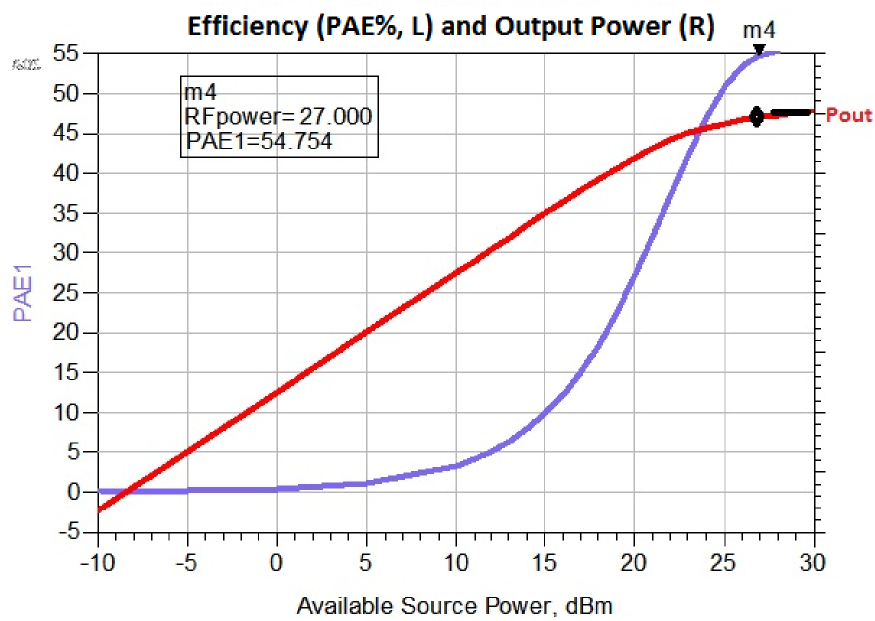

Fig. 20 ADS performance simulation of the ideal broadband (4.5-GHz), 2.4-mm HEMT power amplifier

Table 1 ADS relative performance simulations of the 1.2- and 2.4-mm broadband HEMT power amplifiers

Frequency	2.5 GHz	3.0 GHz	4.5 GHz	6.5 GHz	7.0 GHz
MMIC P_{out}	–1.1 dB, 78%	–0.7 dB, 85%	–0.7 dB, 85%	–0.9 dB, 81%	–1.1 dB, 78%
PAE	48.8%	49.4%	49.6%	42.5%	41.0%
Ideal 1× P_{out}	–0.9 dB, 81%	–0.6 dB, 87%	0 dB, 100%	–0.3 dB, 93%	–0.4 dB, 91%
PAE	57.0%	54.8%	56.5%	59.1%	59.3%
Ideal 2× P_{out}	–0.8 dB, 83%	–0.4 dB, 91%	0 dB, 100%	–0.3 dB, 93%	–0.4 dB, 91%
PAE	55.5%	53.2%	54.8%	57.6%	57.7%

Losses for the MMIC output match were calculated to be a reasonable 0.3 dB over most of the band, with up to a 0.5-dB loss at the low end of the band, 2.5 to 3 GHz. Additional losses on the MMIC input match would similarly affect small signal gain and PAE. The performance data were typically 3 to 4 dB compressed for the Class A/B, biased power amplifier. For the ideal, 2.4-mm power amplifier, the input power level is 3 dB higher, corresponding to a 3-dB higher output power, with the same large signal gain as the ideal, 1.2-mm power amplifier. Nominal performance for the MMIC 1.2-mm HEMT amplifier was within 85% (0.6 dB) of expected output power with 50% PAE at 4.5 GHz. In comparison, the ideal version of the 1.2-mm power amplifier was 100% (0 dB) of expected output power with 57% PAE. As expected the 2-way combined, ideal amplifier has double the output power with similar bandwidth and efficiency, showing double the power of a single 1.2-mm HEMT with 55% PAE at a comparable gain compression level.

3. Summary and Conclusion

A preliminary design of a broadband, 1.2-mm HEMT power amplifier and a 2.4-mm HEMT power amplifier using Raytheon's GaN process was performed. The intent was to explore the bandwidth and performance of a Class A/B, biased, 1.2-mm HEMT power amplifier designed to maximize bandwidth, output power, and PAE over the 2- to 8-GHz band. Trying to increase the band to 2 to 10 GHz would certainly require more matching losses to extend the bandwidth. A similar 2-way combined, 2.4-mm HEMT power amplifier should achieve comparable performance based on a preliminary design using ideal, lossless matching elements. For the one-stage, 1.2-mm HEMT design, a preliminary layout was implemented, including EM simulations of critical elements such as the folded coupled line for the broadband input match.

These designs illustrate broadband, Class A/B power amplifiers using a 1.2-mm HEMT cell, which should provide good efficiency with matching network losses within 0.6 dB of ideal at these frequencies at the recommended DC bias. To get these designs ready for fabrication would require additional steps to pass DRC and LVS checks, perform full EM simulations, simulate process variation effects, and perform normalized determinant function stability analyses.

The Raytheon process is very capable for high-power RF amplifiers and robust low-noise amplifiers for receivers.

List of Symbols, Abbreviations, and Acronyms

ADS	Advanced Design System (CAD tool)
ARL	US Army Research Laboratory
CAD	computer-aided design
DC	direct current
DRC	design rule checks
EM	electromagnetic
GaN	gallium nitride
HEMT	high-electron mobility transistor
LVS	layout versus schematic
MMIC	monolithic microwave integrated circuit
MWO	Microwave Office (CAD tool)
PAE	power-added efficiency
PDK	process design kit
RF	radio frequency

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